

Phenomenology of photon and di-lepton production in relativistic nuclear collisions

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Abstract

We discuss the latest theoretical results on direct photon and dilepton production from relativistic heavy-ion collisions. While the dilepton spectra at low invariant mass show in-medium effects like a collisional broadening of the vector meson spectral functions, the dilepton yield at high invariant masses (above 1.1 GeV) is dominated by QGP contributions for central heavy-ion collisions at relativistic energies. The present status of the photon v_2 "puzzle" – a large elliptic flow v_2 of the direct photons experimentally observed at RHIC and LHC energies – is also addressed. The role of hadronic and partonic sources for the photon spectra and v_2 is considered as well as the possibility to subtract the QGP signal from the experimental observables.

Keywords: Photons, dileptons, heavy-ion collisions

1. Introduction

Electromagnetic probes - real photons and di-lepton pairs - are one of the most promising probes of the Quark-Gluon-Plasma (QGP) formed in ultra-relativistic collisions of heavy ions [1]. They also provide information about the modification of hadron properties in the dense and hot hadronic medium which can shed some light on chiral symmetry restoration (cf. [2] and references therein). The major advantages are related to the fact that dileptons and real photons are emitted from different stages of the reaction and are very little effected by final-state interactions; they provide almost undistorted information about their production channels. However, there are disadvantages, too, due to the low emission rate; the production from the hadronic corona as well as the existence of many production sources, which cannot be individually disentangled by experimental data. For an experimental review on the dilepton and photon measurements at SPS, RHIC and LHC energies see Ref. [3].

Since dileptons and photons are emitted over the entire history of the heavy-ion collision, from the initial hard nucleon-nucleon scatterings through the hot and dense (partonic) phase and to the hadron decays after freeze-out, it is very important to model properly the full time evolution of heavy-ion collisions. For that the dynamical models - microscopic transport or hydrodynamical approaches - have to be applied for disentangling the various sources that contribute to the final observables measured in experiments.

2. Modeling of photon/dilepton emission rates

I. The equilibrium emission rate of electromagnetic probes from thermal field theory can be expressed as [4, 5]:

1) for photons with 4-momentum $q = (q_0, \vec{q})$:

$$q_0 \frac{d^3 R}{d^3 q} = - \frac{g_{\mu\nu}}{(2\pi)^3} \text{Im} \Pi^{\mu\nu}(q_0 = |\vec{q}|) f(q_0, T); \quad (1)$$

2) for dilepton pairs with 4-momentum $q = (q_0, \vec{q})$, where $q = p_+ + p_-$ and $p_+ = (E_+, \vec{p}_+)$, $p_- = (E_-, \vec{p}_-)$:

$$E_+ E_- \frac{d^3 R}{d^3 p_+ d^3 p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{q^4} L_{\mu\nu} \text{Im} \Pi^{\mu\nu}(q_0, |\vec{q}|) f(q_0, T). \quad (2)$$

Here the Bose distribution function is $f(q_0, T) = 1/(e^{q_0/T} - 1)$; $L_{\mu\nu}$ is the electromagnetic leptonic tensor, $\Pi^{\mu\nu}$ is the retarded photon self-energy at finite temperature T related to the electromagnetic current correlator $\Pi^{\mu\nu} \sim i \int d^4 x e^{ipx} \langle [J_\mu(x), J_\nu(0)] \rangle|_T$. Using the Vector-Dominance-Model (VDM) $\text{Im} \Pi^{\mu\nu}$ can be related to the in-medium ρ -meson spectral function from many-body approaches [6] which, thus, can be probed by dilepton measurements directly. The photon rates for $q_0 \rightarrow 0$ are related to the electric conductivity σ_0 which allows to probe the electric properties of the QGP [7]. We note that Eqs.(1),(2) are applicable for systems in thermal equilibrium, whereas the dynamics of heavy-ion collisions is generally of non-equilibrium nature.

II. The non-equilibrium emission rate from relativistic kinetic theory [5, 8], e.g. for the process $1 + 2 \rightarrow \gamma + 3$, is

$$q_0 \frac{d^3 R}{d^3 q} = \int \frac{d^3 p_1}{2(2\pi)^3 E_1} \frac{d^3 p_2}{2(2\pi)^3 E_2} \frac{d^3 p_3}{2(2\pi)^3 E_3} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - q) |M_{if}|^2 \frac{f(E_1)f(E_2)(1 \pm f(E_3))}{2(2\pi)^3}, \quad (3)$$

where $f(E_i)$ is the distribution function of i -particle ($i = 1, 2, 3$), which can be hadrons (mesons and baryons) or partons. M_{if} is the matrix element of the reaction which has to be evaluated on a microscopical level. For hadronic interactions One-Boson-Exchange models or chiral models are used to evaluate M_{if} on the level of Born-type diagrams. However, for a consistent consideration of such elementary process in the dense and hot hadronic environment, it is important to account for the in-medium modification of hadronic properties [6], i.e. many-body approaches such as self-consistent G -matrix calculations have to be applied.

3. Photons

3.1. Photon production sources

There are different production sources of photons in $p + p$ and $A + A$ collisions:

1) *Decay photons* – most of the photons seen in $p + p$ and $A + A$ collisions stem from the hadronic decays:

$m \rightarrow \gamma + X$, $m = \pi^0, \eta, \omega, \eta', a_1, \dots$

2) *Direct photons* – obtained by subtraction of the decay photon contributions from the inclusive (total) spectra measured experimentally.

(i) There are a few sources of direct photons at large transverse momentum p_T , so called 'hard' photons: the 'prompt' production from the initial hard $N + N$ collisions and the photons from the jet fragmentations, which are the standard pQCD type of processes. The latter, however, might be modified in $A + A$ contrary to $p + p$ due to the parton energy loss in the medium. In $A + A$ collisions at large p_T there are also photons from the jet- γ -conversion in the QGP and jet-medium photons from the scattering of hard partons with thermalized partons ($q_{hard} + q(g)_{QGP} \rightarrow \gamma + q(g)$).

(ii) At low p_T the photons come from the thermalized QGP as well as from *hadronic* interactions:

- The 'thermal' photons from the QGP arise mainly from $q\bar{q}$ annihilation ($q + \bar{q} \rightarrow g + \gamma$) and Compton scattering ($q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma$) which can be calculated in leading order pQCD [9]. However, the next-to-leading order corrections turn out to be also important [10].

- *Hadronic* sources of photons are related to

1) secondary mesonic interactions as $\pi + \pi \rightarrow \rho + \gamma$, $\rho + \pi \rightarrow \pi + \gamma$, $\pi + K \rightarrow \rho + \gamma, \dots$. The binary channels with π, ρ have been evaluated in effective field theory [12] and used in transport model calculations [13, 14] within the extension for the off-shellness of ρ -mesons due to the broad spectral function. Alternatively, the binary hadron rates (3) have been derived in the massive Yang-Milles approach in Ref. [11] and been often used in hydro calculations.

2) hadronic bremsstrahlung, such as meson-meson (mm) and meson-baryon (mB) bremsstrahlung $m_1 + m_2 \rightarrow m_1 + m_2 + \gamma$, $m + B \rightarrow m + B + \gamma$, where $m = \pi, \eta, \rho, \omega, K, K^*, \dots$ and $B = p, \Delta, \dots$. Here the leading contribution corresponds to the radiation from one charged hadron scattered with the neutral hadron.

3.2. Direct photons: the v_2 'puzzle'

The photon production has been measured early in relativistic heavy-ion collisions by the WA98 Collaboration in S+Au and Pb+Pb collisions at SPS energies [15]. The model comparisons with experimental data shows that the high p_T spectra are dominated by the hard 'prompt' photon production whereas the 'soft' low p_T spectra stem from hadronic sources since the thermal QGP radiation at SPS energies is not large. Moreover, the role of hadronic bremsstrahlung turns out to be very important for a consistent description of the low p_T data as has been found in expanding fireball model calculations [16] and in the HSD (Hadron-String-Dynamics) transport approach [13]. Unfortunately, the accuracy of the experimental data at low p_T did not allow to draw further solid conclusions.

The measurement of photon spectra by the PHENIX Collaboration [17] stimulated a new wave of interest for direct photons from the theoretical side since at RHIC energies the thermal QGP photons have been expected to dominate the spectra. A variety of model calculations based on fireball, Bjorken hydrodynamics, ideal hydrodynamics with different initial conditions and Equations-of-State (EoS) turned out to show substantial differences in the slope and magnitude of the photon spectra (for the model comparison see Fig. 47 of [17] and corresponding references therein).

The recent observation by the PHENIX Collaboration [18] that the elliptic flow $v_2(p_T)$ of 'direct photons' produced in minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is comparable to that of the produced pions was a surprise and in contrast to the theoretical expectations and predictions [19, 20, 21, 22]. Indeed, the photons produced by partonic interactions in the quark-gluon plasma phase have not been expected to show a considerable flow because - in a hydrodynamical picture - they are dominated by the emission at high temperatures, i.e. in the initial phase before the elliptic flow fully develops. Since the direct photon $v_2(\gamma^{dir})$ is a 'weighted average' by the corresponding yields N_i of the elliptic flow of individual sources i : $v_2(\gamma^{dir}) = \frac{\sum_i v_2(\gamma^i) N_i}{\sum_i N_i}$. Thus, a large QGP contribution gives smaller $v_2(\gamma^{dir})$.

A sizable photon v_2 has been observed also by the ALICE Collaboration [23]. None of the theoretical models could describe simultaneously the photon spectra and v_2 which may be noted as a 'puzzle' for theory. Moreover, the PHENIX and ALICE Collaborations have reported recently the observation of non-zero triangular flow v_3 (see [3, 24]). Thus, the consistent description of the photon experimental data remains as a challenge for theory and has stimulated new ideas and developments. Some of them we briefly discuss in the Section 3.3.

3.3. Towards the solution of the photon v_2 'puzzle': theory

3.3.1. Developments in hydrodynamical models

I.) The first hydrodynamical calculations on photon spectra were based on the ideal hydro with smooth Glauber-type initial conditions (cf. [17]). The influence of *event-by-event (e-b-e) fluctuating initial conditions* on the photon observables was investigated within the (2+1)D Jyväskylä ideal hadro model [22] which includes the equilibrated QGP and Hadron Gas (HG) fluids. It has been shown that 'bumpy' initial conditions based on the Monte-Carlo Glauber model lead to a slight increase at high p_T (> 3 GeV/c) for the yield and v_2 which is, however, not sufficient to explain the experimental data – see the comparison of model calculations with the PHENIX data in Figs. 7,8 of [22] and with the ALICE data in Figs. 9,10 of [22].

II.) The influence of *viscous corrections* on photon spectra and anisotropic flow coefficients v_n has been investigated in two viscous hydro models: (3+1)D MUSIC [21] which is based on 'bumpy' e-b-e fluctuating initial conditions from impact parameter dependent Glasma type ('IP-Glasma') and (2+1)D VISH2+1 [25] with 'bumpy' e-b-e fluctuating initial conditions from the Monte-Carlo Glauber model. Both hydros include viscous QGP (with IQCD EoS) and HG fluids and reproduce well the hadronic 'bulk' observables. The photon rate has been modified in [21, 25] in order to account for first order non-equilibrium (viscous) corrections to the standard equilibrium rates (i.e. the thermal QGP [9] and HG [11] rates). It has been found that the viscous corrections only slightly increase the high p_T spectra compared to the ideal hydro calculations while they have a large effect on the anisotropic flow coefficients v_n - see Fig. 9 in [21]. Interesting that the viscous suppression of hydrodynamic flow anisotropies for photons is much stronger than for hadrons. Also the photon v_n are more sensitive to the QGP shear viscosity which serve the photon v_n as a QGP viscometer [25].

III.) Another idea, which has been checked recently within the (2+1)D VISH2+1 viscous hydro model [25], is associated with the generation of '*pre-equilibrium*' flow (see [26]). The idea of 'initial' flow has been suggested in Ref. [27] and modeled as a rapid increase of bulk v_2 in the expanding fireball model which leads to a substantial enhancement of photon v_2 . In a viscous hydro [26] the generation of pre-equilibrium flow has been realized using

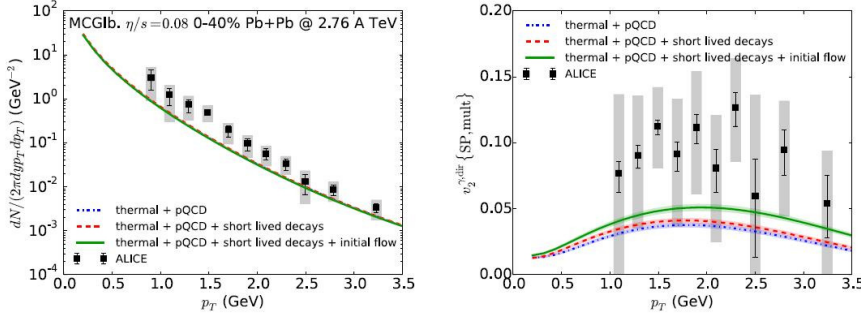


Figure 1. Direct photon p_T -spectrum and elliptic flow coefficient v_2 compared with ALICE measurements in $\sqrt{s} = 2.76$ TeV Pb+Pb collisions at 0-40% centrality [23]. The figure is taken from Ref. [26].

a free-streaming model to evolve the partons to $0.6 \text{ fm}/c$ where the Landau matching takes over to switch to viscous hydro. Such a scenario leads to a quick development of momentum anisotropy with saturation near the critical temperature T_C - see Fig. 1, which shows the direct photon p_T -spectrum (left) and photon v_2 (right) for 40% central Pb+Pb collisions at LHC energies in comparison to the ALICE data [23]. One sees that the pre-equilibrium flow effect increases the photon v_2 slightly but not sufficient to reproduce the ALICE data (the same holds for the PHENIX data). However, the physical origin of 'initial' flow has to be justified/found firstly before robust conclusions can be drawn.

3.3.2. Photons from non-equilibrium transport models

In this Section we depart from the hydro models and consider the influence of *non-equilibrium dynamics* on photon production. As a 'laboratory' for that we will use the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach [30], which is based on the generalized off-shell transport equations derived in first order gradient expansion of the Kadanoff-Baym equations, applicable for strongly interacting system. The approach consistently describes the full evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the strongly-interacting quark-gluon plasma as well as dynamical hadronization and the subsequent interactions in the expanding hadronic phase as in the HSD transport approach [31]. The partonic dynamics is based on the Dynamical Quasi-Particle Model (DQPM), that is constructed to reproduce lattice QCD (lQCD) results for a quark-gluon plasma in thermodynamic equilibrium. The DQPM provides the mean fields for gluons/quarks and their effective 2-body interactions that are implemented in the PHSD (for the details see Ref. [32] and [14, 30]). Since the QGP radiation in PHSD occurs from the massive off-shell quasi-particles with spectral functions, the corresponding QGP rate has been extended beyond the standard pQCD rate [9] - see Ref. [33].

The result for the direct photon p_T -spectra from the PHSD approach [14] is shown in Fig. 2 (left) in comparison to the PHENIX data [18] for midrapidity minimal bias Au+Au collisions at $\sqrt{s} = 200$ GeV. While the 'hard' p_T spectra are dominated by the 'prompt' (pQCD) photons, the 'soft' spectra are filled by the 'thermal' sources: the QGP gives up to 50% of the direct photon yield below 2 GeV/c, the contribution from binary mm reactions is of subleading order. A sizable contribution stems from hadronic sources such as meson-meson (mm) and meson-Baryon (mB) bremsstrahlung, which can be considered as an 'upper estimate' due to the uncertainties in the implementation of photon bremsstrahlung based on the 'soft-photon' approximation (SPA) [5] which implies the on-shell factorization of the amplitude $a + b \rightarrow a + b + \gamma$ into the strong and electromagnetic parts and assumptions on elastic mm and mB cross sections which are little (or not at all) known experimentally (see details in [14]). We stress, that mm and mB bremsstrahlung can not be subtracted experimentally from the photon spectra and, thus, has to be included in theoretical considerations which is not presently the case for hydro results presented above where the 'HG' rate is based on binary mesonic channels $m_1 + m_2 \rightarrow m_3 + \gamma$ [11]. As has been mentioned earlier the importance of bremsstrahlung for 'soft' photons follows also from the WA98 data at $\sqrt{s} = 17.3$ GeV [13, 16], however, more work has to be done to provide robust results on this 'trivial' hadronic source.

3.3.3. Photon sources: QGP vs. HG? Constraints from data.

The question: "what dominates the photon spectra - *QGP radiation or hadronic sources*?" can be addressed experimentally by investigating the centrality dependence of the photon yield: the QGP contribution is expected to decrease from central to peripheral collisions where the hadronic channels are dominant. The right part of Fig. 2 shows the centrality dependence of the direct photon p_T -spectra for 0-20%, 20-40%, 40-60%, 60-92% central Au+Au collisions at $\sqrt{s} = 200$ GeV. The solid dots stand for the recent PHENIX data [28, 29] whereas the lines indicate

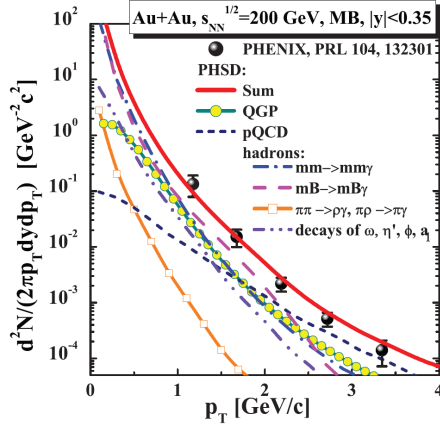
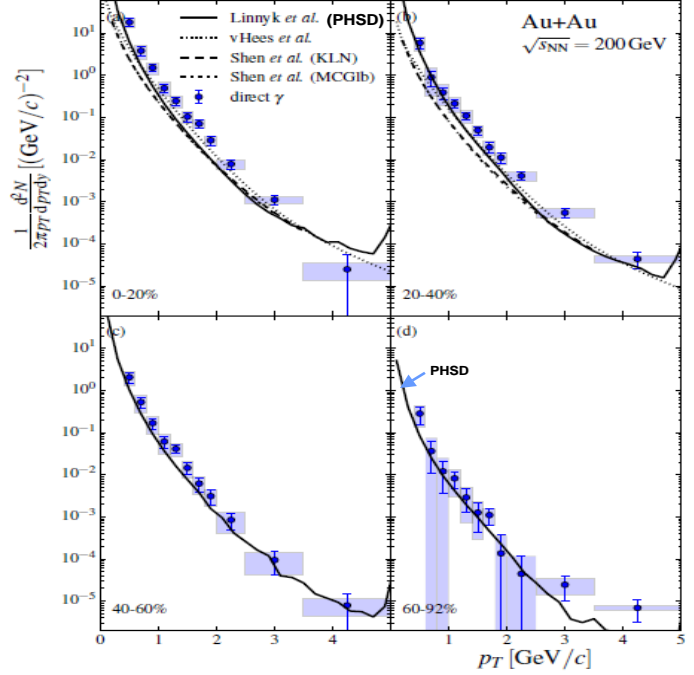


Figure 2. Left: Direct photon p_T -spectrum from the PHSD approach in comparison to the PHENIX data [18] for midrapidity minimal bias Au+Au collisions at $\sqrt{s} = 200$ GeV. The figure is taken from Ref. [14]. Right: Centrality dependence of the direct photon p_T -spectra for 0-20%, 20-40%, 40-60%, 60-92% central Au+Au collisions at $\sqrt{s} = 200$ GeV: model predictions vs. the PHENIX data [28]. The figure is taken from Ref. [29].



the model predictions: solid line - PHSD (denoted as 'Linnyk et al.') [14], dashed and dashed-dotted lines ('Shen et al. (KLN)' and 'Shen et al. (MCGib)') are the results from viscous (2+1)D VISH2+1 [25] and (3+1)D MUSIC [21] hydro models whereas the dotted line ('vHees et al.') stands for the results of the expanding fireball model [27]. As seen from Fig. 2 for the central collisions the models deviate up to a factor of 2 from the data and each other due to the different dynamics and included sources, for the (semi-)peripheral collisions the PHSD results - dominated by mm and mB bremsstrahlung - are consistent with the data which favors these hadronic sources.

The centrality dependence of the direct photon yield, integrated over different p_T ranges, has been measured by the PHENIX Collaboration, too [28, 29]. It has been found that the midrapidity 'thermal' photon yield scales with the number of participants as $dN/dy \sim N_{part}^\alpha$ with $\alpha = 1.48 \pm 0.08$ and only very slightly depends on the selected p_T range (which is still in the 'soft' sector, i.e. < 1.4 GeV/c). Note that the 'prompt' photon contribution (which scales as the pp 'prompt' yield times the number of binary collisions in $A + A$) has been subtracted from the data. The PHSD predictions [14] for the minimal bias Au+Au collisions give $\alpha_{total} = 1.5$ which is dominated by hadronic contributions while the QGP channels scale with $\alpha(QGP) \sim 1.7$. A similar finding has been obtained by the viscous (2+1)D VISH2+1 and (3+1)D MUSIC hydro models [35]: $\alpha(HG) \sim 1.46$, $\alpha(QGP) \sim 2$, $\alpha_{total} \sim 1.7$. Thus, the QGP photons show a centrality dependence significantly stronger than that of HG photons.

Another question: "can one use the photon spectra as a 'thermometer' of the QGP?", i.e. to obtain the temperature of photon sources by extracting the slope parameter from a thermal fit of the photon yields. This question has been answered in a detailed study [35] by the viscous (2+1)D VISH2+1 and (3+1)D MUSIC hydro models where it has been shown that the measured $T_{eff} > \text{'true' } T$ due to the 'blue shift' induced by the strong radial flow. Moreover, it has been shown that only $\sim 1/3$ at LHC and $\sim 1/4$ at RHIC of the total photons come from the 'hot' QCD with $T > 250$ MeV.

Do we see finally the QGP pressure in v_2 if the photon production is dominated by hadronic sources or are the direct photons a 'barometer' of the QGP? As argued in [14] and illustrated in Fig. 3, one can answer the question positively since the QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions. Due to that in PHSD calculations the v_2 of inclusive photons from minimal bias midrapidity Au+Au collisions at $\sqrt{s} = 200$ GeV, which are mainly coming from π_0 decays (blue line in the left part of Fig. 3), is similar to the pion v_2 (red line) and consistent with the PHENIX data, while the HSD results, i.e. without QGP, underestimates the v_2 of inclusive photons (as well as hadrons) by a factor of 2 (dashed line). However, the direct photon v_2 puzzle remains in the PHSD (right part of Fig. 3) due to the very small $v_2(\gamma^{QGP})$ which contributes is up

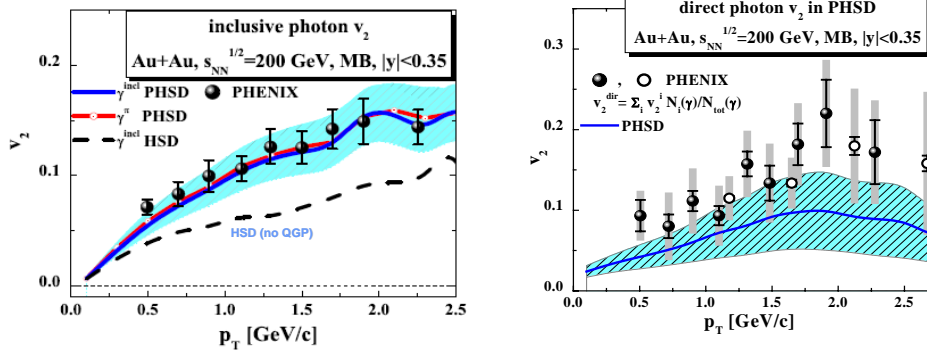


Figure 3. Inclusive (left) and direct (right) photon elliptic flow coefficient $v_2(p_T)$ from the PHSD approach in comparison to the PHENIX data [18] for midrapidity minimal bias Au+Au collisions at $\sqrt{s} = 200$ GeV. The figure is taken from Ref. [14].

to 50% of the total yield. The error band shows the estimated uncertainties related to the mm and mB bremsstrahlung which dominate the direct photon v_2 in PHSD.

We note that there are other scenarios towards the solution of the direct photon v_2 puzzle discussed during the 'Quark Matter-2014' such as early-time magnetic field effects [36], Glasma effects [37], pseudo-critical enhancement of thermal photons near T_C [34] or non-perturbative effects of 'semi-QGP' [38].

4. Dileptons

4.1. Dilepton production sources

Dileptons (e^+e^- or $\mu^+\mu^-$ pairs) can be emitted from all stages of the reactions as well as photons. One of the advantages of dileptons compared to photons is an additional 'degree of freedom' - the invariant mass M which allows to disentangle various sources.

1) Hadronic sources of dileptons in $p + p$, $p + A$ and $A + A$ collisions:

- (i) at low invariant masses ($M < 1$ GeV/c) – the Dalitz decays of mesons and baryons ($\pi^0, \eta, \Delta, \dots$) and the direct decay of vector mesons (ρ, ω, ϕ) as well as hadronic bremsstrahlung;
- (ii) at intermediate masses ($1 < M < 3$ GeV/c) – leptons from correlated $D + \bar{D}$ pairs, radiation from multi-meson reactions ($\pi + \pi, \pi + \rho, \pi + \omega, \rho + \rho, \pi + a_1, \dots$) - so called ' 4π ' contributions;
- (iii) at high invariant masses ($M > 3$ GeV/c) – the direct decay of vector mesons ($J/\Psi, \Psi'$) and initial 'hard' Drell-Yan annihilation to dileptons ($q + \bar{q} \rightarrow l^+ + l^-$, where $l = e, \mu$).

2) 'Thermal' QGP dileptons radiated from the partonic interactions in heavy-ion $A + A$ collisions that contribute dominantly to the intermediate masses. The leading processes are the 'thermal' $q\bar{q}$ annihilation ($q + \bar{q} \rightarrow l^+ + l^-$, $q + \bar{q} \rightarrow g + l^+ + l^-$) and Compton scattering ($q(\bar{q}) + g \rightarrow q(\bar{q}) + l^+ + l^-$).

4.2. Dileptons: from SPS to LHC energies

Dileptons from heavy-ion collisions have been measured in the last decades by the CERES [39] and NA60 [40] Collaborations at SPS energies. The high accuracy dimuon NA60 data provide a unique possibility to subtract the hadronic cocktail from the spectra and to distinguish different in-medium scenarios for the ρ -meson spectral function such as a collisional broadening and dropping mass [2, 41]. The main messages obtained by a comparison of the variety of model calculations (see e.g. [2, 42, 43]) with experimental data can be summarized as (i) low mass spectra [39, 40] provide a clear evidence for the collisional broadening of the ρ -meson spectral function in the hot and dense medium; (ii) intermediate mass spectra above $M > 1$ GeV/c² [40] are dominated by partonic radiation; (iii) the rise and fall of the inverse slope parameter of the dilepton p_T -spectra (effective temperature) T_{eff} [40] provide evidence for thermal QGP radiation; (iv) isotropic angular distributions [40] are an indication for a thermal origin of dimuons.

An increase in energy from SPS to RHIC has opened new possibilities to probe (by dileptons) the matter at very high temperature, i.e. dominantly in the QGP stage, created in central heavy-ion collisions. The dileptons (e^+e^- pairs) have been measured by the PHENIX Collaboration for pp and $Au + Au$ collisions at $\sqrt{s} = 200$ GeV [44]. A large enhancement of the dilepton yield relative to the scaled pp collisions in the invariant mass regime from 0.15 to 0.6 GeV/c² has been observed. This observation has stimulated a lot of theoretical activity (see the model comparison with the data in [44]). The main messages - which stay up-to-now - can be condensed such that the theoretical models,

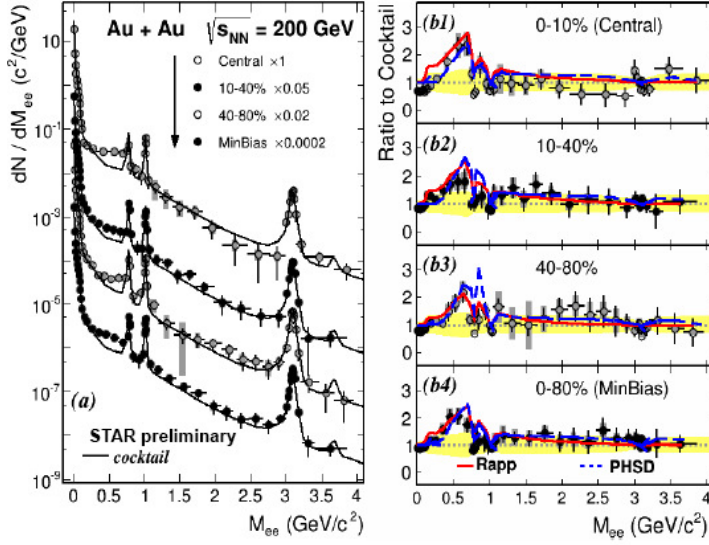


Figure 4. Centrality dependence of the midrapidity dilepton yields (left) and its ratios (right) to the 'cocktail' for 0-10%, 10-40%, 40-80%, 0-80% central Au+Au collisions at $\sqrt{s} = 200$ GeV: a comparison of STAR data with theoretical predictions from the PHSD ('PHSD' - dashed lines) and the expanding fireball model ('Rapp' - solid lines). The figure is taken from Ref. [48].

providing a good description of pp dilepton data and peripheral $Au + Au$ data, fail in describing the excess in central collisions even with in-medium scenarios for the vector meson spectral function. The missing strengths might be attributed to low p_T sources [45]. The intermediate mass spectra are dominated by the QGP radiation as well as leptons from correlated charm pairs ($D + \bar{D}$) [42, 45, 46].

In this respect it is very important to have independent measurements which have been carried out by the STAR Collaboration [47]. Fig. 4 shows the comparison of STAR data of midrapidity dilepton yields (left) and its ratios (right) to the 'cocktail' for 0-10%, 10-40%, 40-80%, 0-80% central Au+Au collisions at $\sqrt{s} = 200$ GeV in comparison to the theoretical model predictions from the PHSD and the expanding fireball model. As seen from Fig. 4 the excess of the dilepton yield over the expected cocktail is larger for very central collisions and consistent with the model predictions based on the collisional broadening of the ρ -meson spectral function and QGP dominated radiations at intermediate masses. Moreover, the recent STAR dilepton data for Au+Au collisions from the Beam Energy Scan (BES) program for the $\sqrt{s} = 19.6, 27, 39$ and 62.4 GeV [3, 48] are also in line with the expanding fireball model predictions with a ρ collisional broadening [48]. According to the PHSD predictions, the excess is increasing with decreasing energy due to a longer ρ -propagation in the high baryon density phase (see Fig. 3 in [3]).

The upcoming PHENIX data for central Au+Au collisions - obtained after the upgrade of the detector - together with the BES-II RHIC data should provide finally a consistent picture on the low mass dilepton excess. The future ALICE data [50] for heavy-ions will give a clean access to the dileptons emitted from the QGP [46, 49].

Last but not least, we mention that promising perspectives with dileptons have been suggested in Ref. [51] - to measure the anisotropic coefficients v_n , $n = 2, 3$ similar to photons. The calculations done with the viscous (3+1)d MUSIC hydro for central Au+Au collisions at RHIC energies show that v_2, v_3 are sensitive to the dilepton sources and to the EoS and η/s ratio. The main advantage of measuring v_n with dileptons compared to photons is the fact that an extra degree of freedom M allows to disentangle the sources. However, this is a very challenging experimental task.

5. Conclusions

I. The main messages from the 'photon adventure' can be summarize in short as: (i) the photons provide a critical test for the theoretical models: the standard dynamical models - constructed to reproduce the 'hadronic world' - fail to explain the photon experimental data; (ii) The details of the hydro models (fluctuating initial conditions, viscosity, pre-equilibrium flow) have a small impact on the photon observables; (iii) as suggested by the PHSD transport model calculations the role of trivial sources such as mm and mB bremsstrahlung has been underestimated and has to be re-considered; (iv) The initial phases of the reaction might turn out to be important (pre-equilibrium /'initial' flow, Glasma effect etc.). Finally one may conclude that the photons are one of the most sensitive probes for the dynamics of HIC and for the role of the partonic phase.

II. The main messages from dilepton data are (i) at low masses ($0.2 - 0.6$ GeV/ c^2) dilepton spectra show sizable changes due to hadronic in-medium effects, i.e. modification of the properties of vector mesons (such as collisional

broadening) in the hot and dense hadronic medium, related to the chiral symmetry restoration; these effects can be observed at all energies from SIS to LHC; (ii) at intermediate masses: the QGP ($q\bar{q}$ thermal radiation) dominates for $M > 1.2 \text{ GeV}/c^2$. The fraction of QGP grows with increasing energy and becomes dominant at the LHC energies.

Finally, the dilepton measurements within the future experimental energy and system scan (pp , pA , AA) from low to top RHIC energies as well as the new ALICE data at LHC energies will extend our knowledge on the properties of hadronic and partonic matter.

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References

- [1] E.L. Feinberg, *Izv. Akad. Nauk Ser. Fiz.* **34**(1970)1987; *Nuovo Cim.* **A34** (1976) 391; E.V. Shuryak, *Phys. Lett.* **B78** (1978) 150.
- [2] R. Rapp, J. Wambach, H. van Hees, in "Relativistic Heavy-Ion Physics", edited by R. Stock, Landolt-Boernstein, Volume I/23, 4-1 (2010).
- [3] L. Ruan, these proceedings, arXiv:1407.8153.
- [4] L. D. McLerran, T. Toimela, *Phys. Rev.* **D31** (1985) 545.
- [5] C. Gale, J. Kapusta, *Phys. Rev. C* **35** (1987) 2107.
- [6] R. Rapp, G. Chanfray, J. Wambach, *Nucl. Phys.* **A617** (1997) 472.
- [7] W. Cassing et al., *Phys. Rev. Lett.* **110** (2013) 182301.
- [8] K. Kajantie, J. Kapusta, L. McLerran, A. Mekjian, *Phys. Rev. D* **34** (1986) 2746.
- [9] P. B. Arnold, G. D. Moore, L. G. Yaffe, *JHEP* **0111** (2001) 057.
- [10] J. Ghiglieri, these proceedings, arXiv:1407.8470.
- [11] S. Turbide, R. Rapp, C. Gale, *Phys. Rev.* **C69** (2004) 014903.
- [12] J. I. Kapusta, P. Lichard, D. Seibert, *Phys.Rev.* **D44** (1991) 2774.
- [13] E. L. Bratkovskaya, S. M. Kiselev, G. B. Sharkov, *Phys. Rev. C* **78** (2008) 034905.
- [14] O. Linnyk et al., *Phys. Rev.* **C88** (2013) 034904; *ibid* **C89** (2014) 034908.
- [15] R. Albrecht et al. (WA98 Collaboration), *Phys. Rev. Lett.* **76** (1996) 3506; M.M. Aggarwal et al., *Phys. Rev. Lett.* **85** (2000) 3595.
- [16] W. Liu, R. Rapp, *Nucl. Phys.* **A 96** (2007) 101.
- [17] A. Adare et al. (PHENIX Collaboration), *Phys. Rev.* **81** (2010) 034911.
- [18] A. Adare et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **109** (2012) 122302.
- [19] R. Chatterjee, E. S. Frodermann, U. W. Heinz, D. K. Srivastava, *Phys. Rev. Lett.* **96** (2006) 202302.
- [20] F.-M. Liu, T. Hirano, K. Werner, Y. Zhu, *Nucl. Phys.* **A 830** (2009) 587c.
- [21] M. Dion et al., *J. Phys.* **G 38** (2011) 124138; *Phys. Rev. C* **84** (2011) 064901.
- [22] R. Chatterjee, H. Holopainen, I. Helenius, T. Renk, K. J. Eskola, *Phys. Rev. C* **88** (2013) 034901.
- [23] D. Lohner et al. (ALICE Collaboration), *J. Phys. Conf. Ser.* **446** (2013) 012028; M. Wilde et al., *Nucl. Phys.* **A 904-905** (2013) 573c.
- [24] F. Bock (for the ALICE Collaboration), these proceedings.
- [25] C. Shen et al., arXiv:1308.2111, arXiv:1403.7558.
- [26] C. Shen et al., these proceedings, arXiv:1407.8533.
- [27] H. van Hees, C. Gale, R. Rapp., *Phys. Rev. C* **84** (2011) 054906.
- [28] A. Adare et al. (PHENIX Collaboration), arXiv:1405.3940.
- [29] S. Mizuno (for the PHENIX Collaboration), these proceedings.
- [30] W. Cassing, E.L. Bratkovskaya, *Phys. Rev. C* **78** (2008) 034919; *Nucl. Phys. A* **831** (2009) 215; *ibid* **A 856** (2011) 162.
- [31] W. Cassing, E.L. Bratkovskaya, *Phys. Rept.* **308** (1999) 65.
- [32] W. Cassing, *Eur. Phys. J. ST* **168** (2009) 3.
- [33] O. Linnyk, *J. Phys. G* **38** (2011) 025105.
- [34] H. van Hees, M. He and R. Rapp, arXiv:1404.2846; R. Rapp, these proceedings, arXiv:1408.0612
- [35] C. Shen et al., *Phys. Rev. C* **89** (2014) 044910.
- [36] G. Basar, D. E. Kharzeev, V. Skokov, *Phys. Rev. Lett.* **109** (2012) 202303; G. Basar, D. E. Kharzeev, E. Shuryak, arXiv:1402.2286.
- [37] L. McLerran, B. Schenke, arXiv:1403.7462.
- [38] S. Lin et al., these proceedings.
- [39] D. Adamova et al. (CERES Collaboration), *Nucl. Phys. A* **715** (2003) 262; *Phys. Lett. B* **666** (2008) 425.
- [40] R. Arnaldi et al. (NA60 Collaboration), *Phys. Rev. Lett.* **96** (2006) 162302; *Eur. Phys. J. C* **61** (2009) 711.
- [41] G. Q. Li, C. M. Ko, G. E. Brown, *Phys. Rev. Lett.* **75** (1995) 4007.
- [42] E. L. Bratkovskaya, W. Cassing, O. Linnyk, *Phys. Lett. B* **670** (2009) 428. O. Linnyk et al., *Phys. Rev. C* **84** (2011) 054917.
- [43] J. Ruppert, T. Renk, *Phys. Rev. C* **71** (2005) 064903; Erratum-ibid. **C 75** (2007) 059901; K. Dusling, D. Teaney, I. Zahed, *Phys. Rev. C* **75** (2007) 024908; E. Santini et al., *Phys. Rev. C* **84** (2011) 014901.
- [44] A. Toia et al. (PHENIX Collaboration), *J. Phys. G* **35** (2008) 104037; A. Adare et al., *Phys. Rev. C* **81** (2010) 034911.
- [45] O. Linnyk et al., *Phys. Rev. C* **85** (2012) 024910.
- [46] R. Rapp, *Adv. High Energy Phys.* **2013** (2013) 148253.
- [47] L. Ruan et al. (STAR Collaboration), *Nucl. Phys. A* **855** (2011) 269; F. Geurts et al., *Nucl. Phys. A* **904-905** (2013) 217c.
- [48] Yi Guo (for the STAR Collaboration), arXiv:1407.6788.
- [49] O. Linnyk et al., *Phys.Rev. C* **87** (2013) 014905.
- [50] M. K. Köhler (for the ALICE Collaboration), these proceedings.
- [51] G. Vujanovic et al., *Phys. Rev. C* **89** (2014) 034904; these proceedings, arXiv:1408.1098.